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HOLOGRAPHIC MEMORIES

After more than 30 years, researchers are on the verge of using holograms to store data in memories that are both fast and vast

Optical storage of data has been one of the bright spots in technology over the past 15 years. Compact discs, for example, dominate the market for musical recordings and are now also the standard medium for multimedia releases, which combine text, images and sound. Video games, entire journals, encyclopedias and maps are among the multimedia products available on CDs to users of personal computers.

Without a doubt, optical memories store huge amounts of digitized information inexpensively and conveniently. A compact disc can hold about 640 million bites--enough for an hour and a quarter of high-fidelity music or more than 300,000 pages of double-spaced, typewritten text. AD indications are, however, that these large memories have stimulated demand for even more capacious and cheaper media. Executives in the entertainment industry would like to put one or more motion pictures on a single optical disk the same size as a CD, and so great are the data storage needs of some hospitals, law firms, government agencies and libraries that they have turned to so-called jukeboxes that have robotic arms to access any one of hundreds of disks.

Engineers have responded by trying to wring the most out of CD systems. Some are working on semiconductor lasers with shorter wavelengths (in effect, these will be finer styli that permit closer spacing of bits on a CD). Others are investigating techniques of data compression and "super-resolution" that also allow higher density (the latter at the expense of increased background noise). Another promising development has been multiple-level CDs, in which two or more data-containing tracks are stacked and read by an optical system that can focus on one level at a time. Such schemes are expected to push the capacity of CDs into the tens of billions of bytes within five years or so.

But to pack a CD-size disk with much more data--hundreds of billions of bytes, say--will require a fundamentally different approach: holography. The idea dates back to 1963, when Pieter J. van Heerden of Polaroid first proposed using the method to store data in three dimensions.

Holographic memories, it is now believed, could conceivably store hundreds of billions of bytes of data, transfer them at a rate of a billion or more bits per second and select a randomly chosen data element in 100 microseconds or less. No other memory technology that offers all three of these advantages is as close to commercialization--a fact that has compelled such large companies as Rockwell, IBM and GTE in the past two years to launch or expand efforts to develop holographic memories.

Initially, the expense and novelty of the technology will probably confine it to a handful of specialized applications demanding extraordinary capacity and speed. Such uses are already attempting to carve out little niches--one recently offered product holographically stores the fingerprints of those entitled to enter a restricted area, permitting access when a matching finger is placed on a glass plate. If in meeting such needs the technology matures and becomes less expensive, it might supersede the optical disk as a high-capacity digital storage medium for general-purpose computing.

The main advantages of holographic storage--high density and speed--come, from three-dimensional recording and from the simultaneous readout of an entire page of data at one time. Uniquely, holographic memories store each bit as an interference pattern throughout the entire volume of the medium.

How Holographic Memories Work

The pattern, also known as a grating, forms when two laser beams interfere with each other in a light-sensitive material whose optical properties are altered by the intersecting beams.

Before the bits of data can be imprinted in this manner in the crystal, they must be represented as a pattern of clear and opaque squares on a liquid crystal display (LCD) screen, a miniature version of the ones in laptop computers. A blue-green laser beam is shined through this crossword-puzzle-like pattern, or page, and focused by lenses to create a beam known as the signal. A hologram of the page of data is created when this signal beam meets another one, called the reference, in the photosensitive crystal. The reference beam, in this case, is collimated, which means that all its light waves are synchronized, with crests and troughs passing through a plane in lockstep (indeed, such waves are known as plane waves). The grating created when the signal and reference beams meet is captured as a pattern of varying refractivity in the crystal.

After being recorded like this, the page can be holographically reconstructed by once again shining the reference beam into the crystal from the same angle at which it had entered the material to create the hologram. As it passes through the grating in the crystal, the reference beam is diffracted in such a way that it re-creates the image of the original page and the information contained on it. The reconstructed page is then projected onto an array of electrooptical detectors that sense the light-and-dark pattern, thereby reading all the stored information on the page at once. The data can then be electronically stored, accessed or manipulated by any conventional computer.

The key characteristic is the accuracy with which the "playback" reference beam must match the original one that recorded the page. This precision depends on the thickness of the crystal-- the thicker the crystal, the more exactly the reference beam must be repositioned. If the crystal is one centimeter thick and the illumination angle deviates by one thousandth of a degree, the reconstruction disappears completely. Far from being an inconvenience, this basic mechanism is exploited in almost all holographic memories. The first page of data is holographically recorded in the crystal. The angle of the reference beam is then increased until the reconstruction of the first hologram disappears. Then a new page of data is substituted and holographically recorded. The procedure, known as angle multiplexing, is repeated many times. Any of the recorded holograms can be viewed by illuminating the crystal with the reference beam set at the appropriate angle.

How many pages can be imprinted into a single crystal? The number is limited mainly by the dynamic range of its material: as more holograms share the same crystalline volume, the strength of each diminishes. Specifically, the percentage of light that is diffracted by each hologram (and therefore sensed by the electro-optical detectors) is inversely proportional to the square of the number of holograms superimposed.

If 10 holograms in a crystal yield a diffraction efficiency equal to 1 percent, 1,000 holograms will have a diffraction efficiency of only 0.0001 percent. This effect determines the maximum number of holograms that can be stored, because the drop in diffraction efficiency ultimately makes the reconstructions too weak to be detected reliably amid the noise in the system--fluctuations in the brightness of the lasers, scattering from the crystal, thermally generated electrons in the detector, and so on. This maximum number of holograms can be determined by measuring the optical properties of the crystal material and the various noise sources in the system. In practice, when the diffraction efficiency has dropped too low for the pages to be reliably reconstructed, the rate at which erroneous data are detected--the bit-error rate--becomes unacceptably high.

Stronger Signals

Much of the work in developing holographic memories comes down to the application of new techniques to strengthen, against the background noise, the optical signals representing pages of data. Better technologies have allowed fainter and fainter signals to be reliably detected, and improvements in holographic recording methods have strengthened the recorded signals, enabling more pages to be imprinted into the crystal.

The first attempts to store many holograms date back to the early 1970s. Juan J. Amodei, William Philips and David L. Staebler of RCA Laboratories recorded 500 holograms of plane waves in an iron-doped lithium niobate crystal. Robert A. Bartolini and others, also at RCA, stored 550 holograms of high-resolution images in a light-sensitive polymer material, and Jean-Pierre Huignard's group at Thomson-CSF in Orsay, France, engineered a memory with 256 locations, each capable of storing 10 holograms. Besides storing relatively many holograms, Huignard's system was exceptionally well engineered.

Impressive though some of these early efforts were, none of them led to a practical system. Semiconductor and magnetic memories were progressing quite rapidly at the time, making more exotic technologies seem unworthy of pursuit. Gradually, holographic memories fell out of the limelight.

A renaissance began in 1991, when one of us (Mok), with funding from the U.S. Air Force and the Department of Defense's Advanced Research Projects Agency, demonstrated the storage and high-fidelity retrieval of 500 high-resolution holographic images of tanks, jeeps and other military vehicles in a crystal of lithium niobate with trace amounts of iron.

Several new theories and experiments followed. In 1992 we stored 1,000 pages of digital data in a one-cubic-centimeter, iron-doped lithium niobate crystal. Each stored page contained 160 by 110 bits obtained from the ordinary electronic memory of a digital personal computer. We then copied segments of the stored data back to the

memory of the digital computer--and detected no errors. This experiment demonstrated for the first time that holographic storage can have sufficient accuracy for digital computers.

A similar setup was used to store 10,000 pages, the most in a single crystal so far. Each of these pages measured 320 bits by 220 bits, so all told the system could store a little less than 100 million bytes (100 megabytes). We performed this experiment in 1993 at the California Institute of Technology in collaboration with Geoffrey Burr.

The majority of the 10,000 stored holograms were random binary patterns, similar to the data that can be stored by a conventional computer. The raw (uncorrected) error rate was one bad bit out of every 100,000 evaluated. Such a rate suffices to store image data, particularly if they have not been compressed or manipulated to reduce the number of bits needed to represent the image. Several photographs of faces and of the Caltech logo were also included among the pages to demonstrate that images and data can be easily combined in a holographic memory. The information contained in the 10,000 holograms would fill only one eighth of the capacity available in a conventional compact disc. But holographic memories that have a much higher capacity can be made by storing holograms at multiple locations in the crystal. For instance, we demonstrated a system in which 10,000 data pages are stored in each of 16 locations, for a total of 160,000 holograms.

In 1994 John F. Heanue, Matthew C. Bashaw and Lembertus Hesselink, all at Stanford University, stored digitized, compressed images and video data in a holographic memory and recalled the information with no noticeable loss of picture quality. They stored 308 pages, each containing 1,592 bits of raw data, in four separate locations in the same crystal. The Stanford group combined several techniques, some electronic, others optical, to keep the bit-error rates under control. For instance, they appended a few bits to each string of eight bits to correct a single erroneous bit anywhere in the group. This error-correcting code reduced the error rate from about one bit in every 10,000 or less to about one bit per million.

Another important potential advantage of holographic storage is rapid random access by nonmechanical means. For example, high-frequency sound waves in solids can be used to deflect a reference light beam in order to select and read out any page of data in tens of microseconds--as opposed to the tens of milliseconds typical of the mechanical-head movements of today's optical and magnetic disks. At Rockwell's research center in Thousand Oaks, Calif., John H. Hong and Ian McMichael have designed and implemented a compact system capable of storing 1,000 holograms in each of 20 locations. An arbitrary page can be accessed in less than 40 microseconds, and its data are retrieved without errors.

Promising Polymers

As with the original experiments in the 1970s, these recent demonstrations used a crystal of lithium niobate with trace amounts of iron. When illuminated with an optical pattern--such as a hologram created by the intersection of two laser beams--charged particles migrate within the crystal to produce an internal electric field whose modulation closely matches that of the optical pattern. The way the crystal then diffracts light depends on this electric field: when the crystal is illuminated again at the correct angle, light is diffracted in such a way that the original hologram is reconstructed. The phenomenon is known as the photo refractive effect [see "The Photorefractive Effect," by David M. Pepper, Jack Feinberg and Nicolai V. Kukhtarev; SCIENTIFIC AMERICAN, October 1990].

A different type of holographic material became commercially available for the first time last year. This material, known as a photopolymer, was developed at Du Pont and undergoes chemical rather than photorefractive changes when exposed to light. Electrical charges are not excited, and the photochemical changes are permanent--information cannot be erased and rewritten. The medium is therefore suitable only for write-once or read-only memories. The material does, however, have a diffraction efficiency 2,500 fumes greater than a lithium niobate crystal of the same thickness. One of us (Psaltis) collaborated with Allen Pu of Caltech and Kevin Curtis of AT&T Bell Laboratories on an experiment in which we stored 1,000 pages of bit patterns in a polymer film 100 microns thick. We retrieved the data without any detected errors.

In recent years, researchers at IBM and at the University of Arizona have begun experimenting with polymer films that, like lithium niobate crystals, exhibit the photorefractive effect. Promising though the developments in polymeric holographic materials are, it is too soon to count out lithium niobate, which has lately also shown greater varsatility. For instance, crystals of lithium niobate doped with trace amounts of both cerium and iron--which are sensitive to red light rather than green--recently became available. They point the way to crystals that can be imprinted with inexpensive and tiny semiconductor lasers, instead of the much more costly green or blue-green ones.

Something Borrowed, Something New

The iron-doped lithium niobate crystals used in the recent demonstrations are not the only surviving aspect of the early experiments more than two decades ago. The argon lasers typically used today are also the same. And angle multiplexing was relied on in the past, as now. What changes, then, have revived holographic data storage?

The most significant advance has been the emergence of a mature optoelectronics industry, which has produced the inexpensive, compact and power-efficient devices needed to build large-scale holographic memories and to interface them with digital computers. For instance, tiny semiconductor lasers that emit red light, originally developed for fiber-opt/c communications, can be used as light sources either with a cerium- and iron-doped lithium niobate crystal or with Du Pont's photopolymer. Large detector arrays made for television cameras, which take an optical image and convert it to an electronic signal, read the output of the memory. Liquid-crystal display screens originally designed for video projectors serve as the input devices, creaking the bright-and-dark patterns that represent pages of data.

Such technological advances made possible the recent memory demonstrations that, in turn, prompted new investigations into the underlying physics. For example, a long-standing problem in holographic memories is cross talk

noise--the partial, spontaneous and unwanted readout of stored data. In practice, cross talk causes faint, ghostlike images of all the pages to be called up when only one is being accessed. Cross-talk noise and its sources are now completely understood, allowing us to calculate and counteract the effect in any recording setup from such parameters as the angle between the signal and reference beams, the angle between the reference beams in a multiplexed recording and the geometric properties of the page of data.

Another by-product of the theoretical work has been the development of new multiplexing methods and the refinement of existing ones. These can replace or supplement angle multiplexing, giving the system designer more options. In one alternative, pursued separately at Pennsylvania State University and at Caltech, successive pages are recorded with reference beams of different wavelengths. Reference beams that are coded with a different pattern for each page have also been demonstrated at the University of California in San Diego and, independently, at the Optical Institute in Orsay, France.

Increasing the Volume

Better multiplexing techniques are certainly welcome, but a fundamental means of increasing capacity will be needed if holographic memories are to make inroads against compact discs. Holographic memories have been shown to be significantly faster at present than are compact-disc systems, but speed alone is rarely enough for a new technology to supplant an entrenched one. What is generally needed is another basic advantage, such as greater storage capacity.

One way to increase storage in a holographic memory would be to tile a two dimensional surface with sugar-cube like memory crystals, a technique called spatial multiplexing. As expected, the capacity of such a system is proportional to the number of cubes. Data are stored in each of the cubes in the usual way, as angle-multiplexed holograms.

The challenging part of this kind of system is the optical assembly, which must be capable of addressing any one of the cubes individually. One such assembly is the three-dimensional disk, which has many similarities to a conventional CD. The disk-shaped recording material is placed on a rotating stage; a laser-based reading and writing device, or head, is mounted above it. The rotation of the disk and radial scanning of the head make it possible to illuminate any spot on the disk. Psalhs proposed the idea in 1992; Pu built a system based on it earlier this year at Caltech.

As in any holographic medium, data are stored throughout the volume of the recording layer of the 3-D disk. The head has a detector 'array for reading out an entire page of data and a beam deflector for angle multiplexing. A spatial-light modulator, which imprints the page of data onto the signal beam (such as the LCD screen used in current demonstrations), could also be incorporated into the head.

Even though a 3-D disk stores information in three dimensions, the number of bits that could theoretically be stored per square micron of disk surface can be computed for the purpose of comparing this areal density to that of a conventional CD. Such a comparison is reasonable because a 3-D disk can be as thin as a CD. It turns out that for thicknesses less than two millimeters, the areal density of the holographic disk is approximately proportional to the thickness of the recording medium. In his demonstration at Caltech, Pu achieved a surface density of 10 bits per square micron in a disk made with a polymer film 100 microns thick (the maximum available for this particular material). This density is about 10 fumes that of a conventional CD.

We can increase the surface density, moreover, by simply increasing the thickness of the holographic layer. Density of 100 bits per square micron would be possible with a material one millimeter thick. Such a 3-D disk would be nearly identical in size and weight to a conventional CD, but it would store 100 fumes more information.

Among the companies pursuing this basic technology is Holoplex, a small start-up that we co-founded in Pasadena, Calif. The company has built a high speed memory system capable of storing up to 1,000 fingerprints, for use as a kind of selective lock to restrict access to buildings or rooms. Although the capacity of this system is approximately half that of a CD, its entire contents can be read out within one second. Holoplex is now working on another product that would be capable of storing up to a trillion bits, or almost 200 times what can be put on a CD.

Memory by Association

Before such a "super CD" becomes a commercial reality, holographic memories may be used in specialized, high-speed systems. Some might exploit the associative nature of holographic storage, a feature first expounded on in 1969 by Dennis Gabor, who was awarded the 1971 Nobel Prize for Physics for the invention of holography.

Given a hologram, either one of the two beams that interfered to create it can be used to reconstruct the other. What this means, in a holographic memory, is that it is possible not only to orient a reference beam into the crystal at a certain angle to select an individual holographic page but also to accomplish the reverse. Illuminating a crystal with one of the stored images gives rise to an approximation of the associated reference beam, reproduced as a plane wave emanating from the crystal at the appropriate angle.

A lens can focus this wave to a small spot whose lateral position is determined by the angle and therefore reveals the identity of the input image. If the crystal is illuminated with a hologram that is not among the stored patterns, multiple reference beams--and therefore multiple focused spots, are the result. The brightness of each spot is proportional to the degree of similarity between the input image and each of the stored patterns. In other words, the array of spots is an encoding of the input image, in terms of its similarity with the stored database of images.

Earlier this year at Caltech, Pu, Robert Denkewalter and Psaltis used a holographic memory in this mode to drive a small car through the corridors and laboratories of the electrical engineering building there. We stored selected images of the hallways and rooms in a holographic memory connected to a digital computer on a laboratory bench and communicated them to the car via a radio link. A television camera mounted on the car provided the visual input. As the

car maneuvered, the computer compared images from the camera with those in the holographic memory [see illustration on preceding two pages]. Once it spied a familiar scene, it guided the vehicle along one of several prescribed paths, each defined as a sequence of images recalled from the memory. Some 1,000 images were stored in the memory, but only 53 were needed, it was found, to navigate through several rooms in the building.

We are now designing a different vehicle, which we hope to equip with a large enough memory to travel autonomously anywhere on the campus. Even with so much capacity, the parallelism of the holographic memory would permit stored information to be called up rapidly enough to let the vehicle follow roads and avoid obstacles. Indeed, navigation may be one of the specialized applications that generates the impetus needed to bring the technology into widespread use.

Such acceptance may be years away. But as the need to store vast amounts of data increases, so, too, will the expediency of storing the information in three dimensions rather than two.

PHOTO (COLOR): HOLOGRAPHIC MEMORY stores data in a crystal of lithium niobate not much larger than a sugar cube (foreground). The hologram is created in the crystal by the meeting of a reference laser beams, shown thick and bright in this photograph, and a signal beam, fainter and thinner, which contains the data.

DIAGRAM: OPTICAL LAYOUT shows how a crystal of lithium niobate can be imprinted with pages of data. One laser beam, known as the signal, takes on the data as it passes through a spatial-light modulator, which displays pages as a crossword-like pattern. This beam meets another, called the reference, in the crystal, which records the resulting interference pattern. A mechanical scanner changes the angle of the reference beam before another page can be recorded. Any stored page can be retrieved by illuminating the hologram with the reference beam used to record it. The reconstructed page is read by charge coupled devices, which produce a current in response to light.

PHOTOS (COLOR): VEHICLE STEERED BY HOLOGRAMS navigated itself around the authors' laboratory at the California institute of Technology. Each compound photograph in this sequence shows what a video camera on the vehicle saw (main image), along with another image (inset) that was transmitted to the little machine from a holographic memory. To navigate, the vehicle

PHOTO (COLOR): (shown above) oriented itself until its camera image matched the one from its memory. Lights in the other, smaller inset indicate the extent to which two image sequences are in synchrony. In this series, the vehicle initially recognized and approached a bicycle. It was then prompted by the image it would see after a left turn, which it found after a bit of searching.

PHOTO (COLOR): HOLOGRAPHIC LOCK stores up to 1,000 fingerprints. To gain entry to a room, a user places a finger on a glass plate. The fingerprint must match one of those in the memory, which are stored as holograms. The fast memory minimizes the delay while the system searches for a match. This type of device is being developed by the Japanese company Hamamatsu. It uses the holographic memory shown here from Holoplex, a Pasadena, Calif., start-up company co-founded by the authors.

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